



Non-perturbative Heavy-Flavor Transport at RHIC and LHC

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Abstract

We calculate open heavy-flavor (HF) transport in relativistic heavy-ion collisions by applying a strong-coupling treatment in both macro- and microscopic dynamics (hydrodynamics and non-perturbative diffusion interactions). The hydrodynamic medium evolution is quantitatively constrained by bulk and multi-strange hadron spectra and elliptic flow. The heavy quark (HQ) transport coefficient is evaluated from a non-perturbative T -matrix approach in the Quark-Gluon Plasma (QGP) which, close to the critical temperature, leads to resonance formation and feeds into the recombination of heavy quarks on a hydrodynamic hypersurface. In the hadronic phase, the diffusion of HF mesons is obtained from effective hadronic theory. We compute observables at RHIC and LHC for non-photonic electrons and HF mesons, respectively.

Keywords: Heavy Quark, Quark-Gluon Plasma, Heavy-ion Collisions, Non-perturbative Diffusion

1. Introduction

A deconfined state of nuclear matter has been predicted by large-scale numerical simulations of Quantum Chromodynamics (QCD) on the lattice [1, 2]. Utilizing ultra-relativistic heavy-ion collision (URHIC) experiments, this new phase has been identified as a strongly coupled Quark-Gluon Plasma (sQGP) [3, 4]. With the advent of LHC, the endeavor of characterizing the properties of sQGP has entered a new stage [5, 6].

Heavy quarks, due to their large masses ($m_c \simeq 1.3$ GeV for charm and $m_b \simeq 4.2$ GeV for bottom), are produced in primordial hard collisions [7], and their number is expected to be conserved in the subsequent evolution of the medium. Through interactions with medium constituents, the spectra of HQs are modified, yet they may not fully thermalize. This makes them valuable probes of the hot and dense matter created in URHICs [8]. The suppression of non-photonic electrons (e^\pm) from HF decays measured in Au+Au ($\sqrt{s_{NN}} = 200$ GeV) at RHIC [9, 10, 11] is surprisingly large, and their elliptic flow [10, 11] indicates a substantial collectivity of charm quarks. It is difficult to explain these results within perturbative QCD approaches [12, 13, 14, 15] for HQ scattering in the QGP. They rather indicate the need for a non-perturbative treatment of HQ diffusion in the low- and intermediate-momentum region [16].

Here, we report on applications of our recently developed non-perturbative framework for open HF transport in medium [17] to D - and B -meson observables at LHC, and predict upcoming RHIC data for flavor-separated e^\pm spectra.

2. Theoretical Framework: HQ Transport and Hadronization

The kinetics of HQs in the QGP can be described by Fokker-Planck dynamics, which in practice is simulated through relativistic Langevin diffusion [8]. The required transport coefficient is the HQ thermal relaxation rate,

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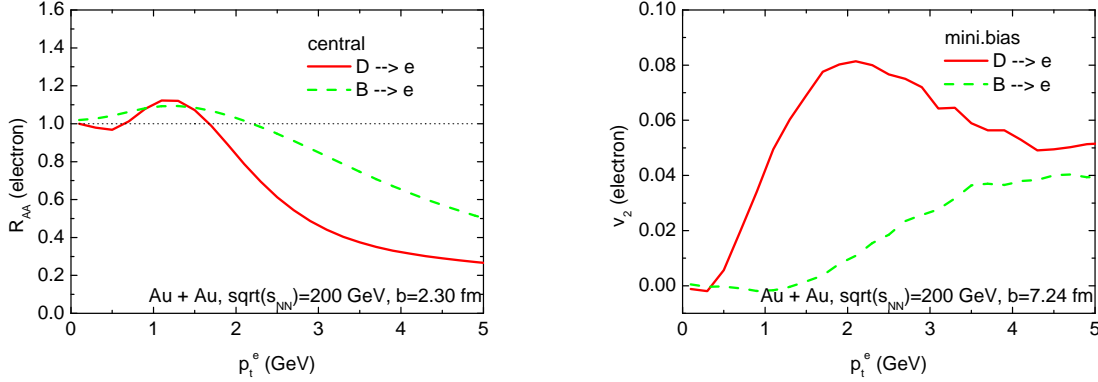


Figure 1: (Color online) Separate charm- and bottom-electron R_{AA} (left panel) and v_2 (right panel) in Au+Au ($\sqrt{s_{NN}}=200$ GeV).

$A(p, T)$. We employ the results from a thermodynamic T -matrix approach [18] for HQ-light quark scattering with input potentials taken as the HQ internal energy computed in thermal lattice QCD. While HQ-gluon scattering was treated perturbatively in Refs. [17, 19], we here adopt a recent update also computed in the T -matrix formalism [20]. The T -matrices exhibit resonant states close to threshold at temperatures $T \approx 1 - 1.5 T_c$, which accelerates the HQ thermal relaxation by a factor of $\sim 3-5$ for the HQ-light quark scattering (factor ~ 2 for HQ-gluon) over leading order pQCD results [18]. After hadronization, the open HF mesons continue to diffuse in the hadronic fluid. The thermal relaxation rate of D mesons has been calculated by using elastic scattering amplitudes from effective hadronic theory [21]. As summarized in Ref. [19], the charm diffusion coefficient $\mathcal{D}_s = T/[m_{c,D}A(p=0, T)]$ is essentially continuous across the phase transition region, possibly indicative of “quark-hadron duality”. The B -meson thermal relaxation rate used is obtained from that of D mesons by scaling the relevant mass, assuming they have the same spatial diffusion coefficient (in the large mass limit).

The Langevin simulations of HQ diffusion in QGP are implemented into the space-time evolution of a background medium modeled by boost-invariant ideal hydrodynamics [22]. The equation of state (EoS) was constructed from a parameterization of recent lattice-QCD data in the high temperature phase [23, 2], combined with a partial chemical-equilibrium EoS for the hadronic phase. A compact initial-density profile with pre-equilibrium flow was introduced resulting in fair fits to multistrange-hadron observables close to the transition temperature, $T_c = 170$ MeV, and to bulk-hadron observables at $T_{kin} = 110$ MeV. Further details of the implementation of the Langevin simulation can be found in Ref. [17].

At $T_c = 170$ MeV, the heavy quarks are hadronized into HF mesons. We accomplish this by first applying resonance recombination [24, 17] with thermal light quarks on the pertinent hydro-hypersurface. Remaining heavy quarks are treated with δ -function fragmentation (as used in the fits to baseline HQ spectra in p+p collisions). For a reliable recombination dynamics at low and intermediate transverse momenta, p_T , it is crucial that the correct thermal equilibrium limit is respected. We have verified this in the presence of the full space-momentum correlations generated from the HQ Langevin dynamics and hydrodynamic flow of the thermal light quarks. The relative partition between recombination and fragmentation is determined by a coalescence probability which is obtained from the HQ T -matrix scattering rate, and thus consistent with the underlying transport coefficient [17]. At T_c , the in-medium quark and meson masses are used: $m_q = 0.3$ GeV, $m_c = 1.7$ GeV, $m_b = 5.2$ GeV, $m_D = 2.1$ GeV and $m_B = 5.6$ GeV, with D - and B -meson widths of $\Gamma_{D,B} = 0.1$ GeV. After hadronization, the Langevin simulation resumes for D and B mesons in the hadronic phase until hydrodynamic kinetic freezeout at $T_{kin} = 110$ MeV.

3. Open Heavy-Flavor Observables

3.1. Flavor-separated non-photonic electrons at RHIC

The measured e^\pm nuclear suppression factor, R_{AA} , and elliptic flow, v_2 , for Au+Au ($\sqrt{s_{NN}}=200$ GeV) collisions thus far are superpositions of open-charm and -bottom contributions [9, 10, 11]. In anticipation of experimental

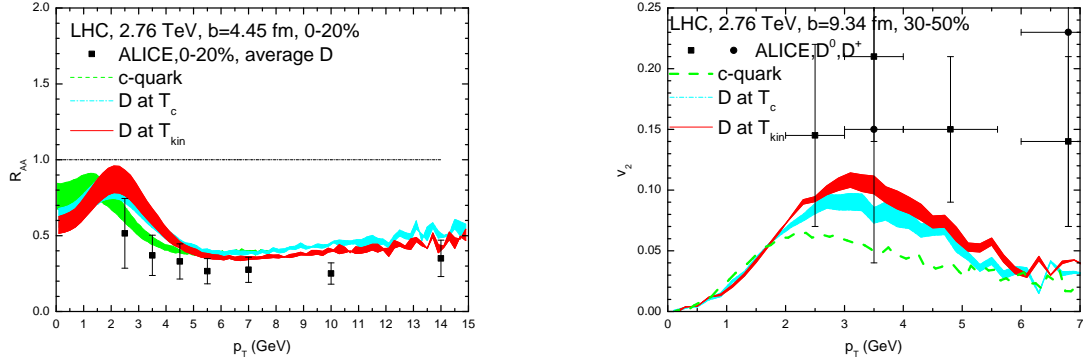


Figure 2: (Color online) D -meson R_{AA} (left panel) and v_2 (right panel) in Pb+Pb ($\sqrt{s_{NN}}=2.76$ TeV) collisions, compared to ALICE data [28, 29]. Our results for charm quarks, D mesons after hadronization at T_c and after hadronic diffusion at T_{kin} , are shown separately. The bands indicate the prevalent uncertainties in each case: shadowing (64.0%-77.6%) for R_{AA} and charm-quark coalescence probability (50%-90%) for v_2 .

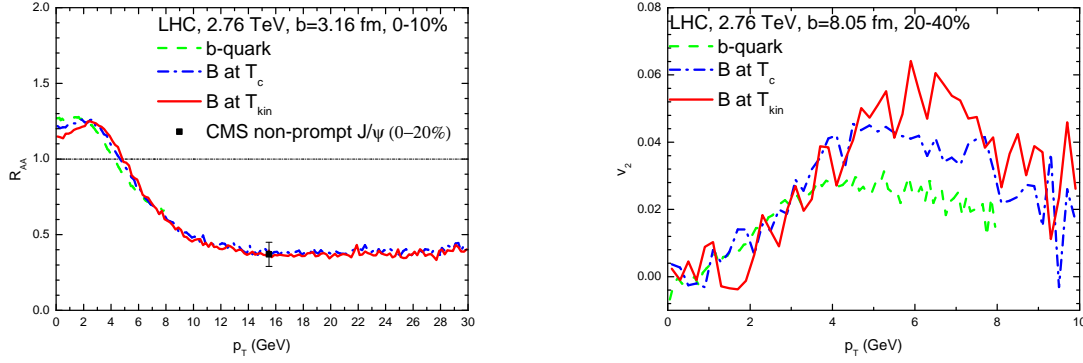


Figure 3: (Color online) B -meson R_{AA} (left panel) and v_2 (right panel) for Pb+Pb ($\sqrt{s_{NN}}=2.76$ TeV) collisions. No shadowing is assumed. The average p_T of the CMS datum [30] on non-prompt J/ψ has been rescaled by $m_B/m_{J/\psi}$.

results for charm- and bottom-separated e^\pm [25], we present in Fig. 1 our pertinent predictions. The charm- e^\pm R_{AA} exhibits a flow bump at $p_t^e \simeq 1.5$ GeV, which is a combined consequence of charm-quark thermalization in the QGP diffusion processes and the subsequent coalescence with thermal light quarks at hadronization [17]. Note that, from a microscopic point of view, both processes are of identical origin (heavy-light quark T -matrix). At $p_t^e \simeq 5$ GeV, the charm e^\pm suppression reaches 0.2-0.3. In accord with approaching thermalization in the suppression factor, the charm- e^\pm also acquires substantial elliptic flow, reaching $\sim 8\%$ at $p_t^e \simeq 2$ GeV. Bottom electrons suffer less suppression, at least below $p_t^e \simeq 5$ GeV, due to the larger b -quark mass. We also observe the bottom- e^\pm v_2 to saturate at a significantly larger p_t^e than for charm, as a result of the larger m_b/m_q ratio that is operative in picking up light-quark v_2 through coalescence.

3.2. D and B mesons at LHC

Next, we apply our non-perturbative approach to the LHC. Toward this end, we employ FONLL pQCD [26] D_0 -meson and B -meson spectra in $\sqrt{s} = 2.76$ TeV p+p collisions as our baseline, which yield good agreement with the ALICE D_0 spectrum [27]. Assuming δ -function fragmentation and folding with EPS09 shadowing [28], we obtain our initial HQ spectra for the Langevin simulations. The hydrodynamic medium evolution model has been tuned to available hadron data at the respective centralities, reproducing fairly well charged-hadron multiplicities, spectra and v_2 at T_{kin} , and Ω^- observables at T_c .

In Fig. 2 we display our calculated D -meson R_{AA} and v_2 for central and semi-central collisions, respectively. The flow bump in the c -quark R_{AA} at low p_T is amplified via coalescence at the D -meson level. Diffusion of D mesons in

the hadronic phase slightly reduces the D -meson R_{AA} at high p_T , and increases the v_2 by up to 20%. Our D -meson R_{AA} appears to be systematically slightly too high but it reproduces the p_T -shape of the data [28] rather well, largely induced by the falling momentum-dependence of the non-perturbative c -quark relaxation rate [18, 20]. The deviation from the data possibly indicates a missing radiative energy-loss contribution. For the D -meson v_2 we note that c -quark diffusion through the QGP only accounts for about half of its final value. Coalescence with light quarks and D -meson diffusion in hadronic phase cannot be neglected. Again, the apparent underprediction of the ALICE data, especially at higher p_T where the momentum-dependence of the elastic c -quark relaxation rate drops significantly, might call for an inclusion of radiative contributions. We note that such an assessment is only possible in the absence of phenomenological K -factors.

The B -meson results, shown in Fig. 3, show a substantial suppression of $R_{AA} \simeq 0.4$ at $p_T > 10$ GeV, while the v_2 , reaching up to 5%, indicates less collectivity (and thus less thermalization) than for D 's. The B -meson modifications also impact J/ψ 's via a so-called “non-prompt” feeddown. In this context it is interesting to quote the suppression of non-prompt J/ψ of the CMS collaboration [30], which is $\sim 0.37 \pm 0.08$ at an average $p_T^{J/\psi} \simeq 9.3$ GeV, in good agreement with our B -meson result at a correspondingly somewhat larger parent momentum.

4. Conclusions

We have evaluated heavy-flavor probes at RHIC and LHC within a non-perturbative framework for bulk evolution and microscopic interactions in the diffusion process [17]. Initial comparisons to e^\pm , D - and B -meson observables at RHIC and LHC are encouraging.

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